Modeling Fluid-Structure Interaction

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LONG-TERM GOALS

We are approaching the end of our second year on this research project. We are working on the development of an integrated analytical-experimental effort to develop a physics based reduced order analytical model of the nonlinear fluid-structure interactions in articulated naval platforms. Environmental effects include forces due to waves, current, and vortex shedding. The symbiosis of analysis and experiments provides a unique opportunity to advance the state of the art in such analytical modeling by directly addressing nonlinear coupling effects, and linking individual terms in the analysis to physical parameters measured in the laboratory. This research is also an excellent vehicle for training a new generation of workers who are adept at understanding fluid-structure interaction problems both from analytical dynamics and experimental fluid dynamics perspectives.

OBJECTIVES

Our objectives include the following: (i) to develop a first-principles-based approach to the development of reduced order differential equations governing the coupled and nonlinear interaction between shedding vortices and structural response, and (ii) to examine bending and extension in long and slender beams subject to vortex shedding, buoyancy, and wave loads. The work is coupled in that there is close collaboration between the structural and fluid mechanicians. Specifically, the reduced order analytical model that is being developed includes terms that require experimental input. Guidance and validation are proceeding in tandem.

APPROACH

Our approach entails examining identical model problems both experimentally and analytically. The structural equations are derived using the methods of analytical mechanics and Newton's second law of motion. The methods of the variational calculus provide us an excellent framework for these analytical derivations as well as for experimental input. Implicit in these derivations is a coupling with the surrounding fluid. Coupling is due to buoyancy effects, added mass, and the relative motion between structure and fluid. Ongoing experiments are described in the following section.

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WORK COMPLETED

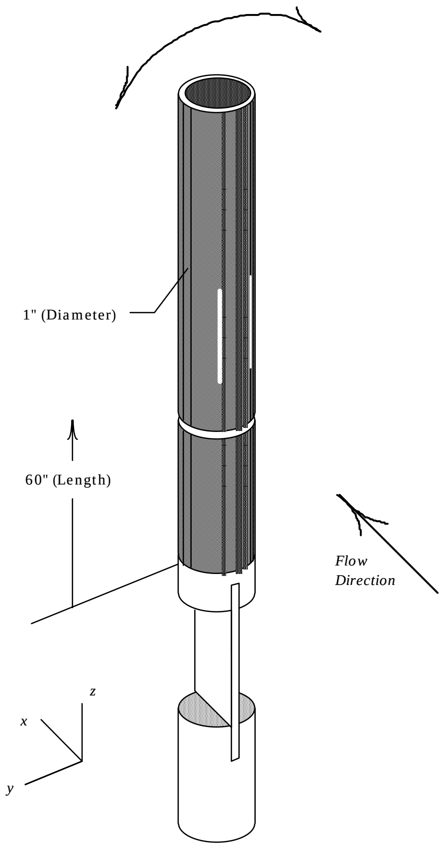
A joint analytical-experimental investigation is in progress to advance the state-of-the-art in reduced order modeling of fluid-structure interactions. The specific modeling problem is that of a rigid circular cylinder which is hinged at the base and immersed in a steady flow of water. By allowing the cylinder to freely move in the cross-stream direction, the nonlinear coupling of structural motion to vortex induced fluid loading can be investigated and modeled. The analytical dynamic modeling uses an energy based Hamilton's Principle approach coupled to an integral fluid kinetic energy transport equation. High resolution, video-based flowfield measurement techniques are being employed to directly measure key terms in the governing equations of motion. Experiments to date include two color Laser Induced Fluorescence (LIF) flow visualization studies of the fluid-structure interaction at and around lock-in, along with Digital Particle Image Velocimetry (DPIV) measurements which provide insight into the dynamics of the fluid-structure coupling. In addition, a new high-resolution video based technique for measuring fluid acceleration, Digital Particle Image Accelerometry (DPIA) has been developed and implemented in this investigation. A brief overview of key experimental findings is outlined in the following section. Early work, both experimental and analytical, has been presented at the 1998 ASME Fluids Engineering Division Meeting and two archival journal papers (one in the Journal of Fluid Mechanics, and one in the Journal of Sound and Vibration) are currently in review. Additional papers addressing critical issues in this research will be submitted shortly.

RESULTS

Experiments are being conducted in the large Free Surface Water Tunnel facility at Rutgers. A 152 cm long circular cylinder, 2.54 cm in diameter is immersed in the test section, which is filled with water to a 102 cm depth. Schematic drawings of the cylinder and flow facility are shown in Figures 1 and 2, respectively. The cylinder was constructed from sections of thin walled anodized aluminum tubing. It is attached to a plate at the bottom of the test section with a stainless steel leaf spring oriented such that cylinder motions are restricted to the cross-stream plane. The mass ratio of the structure is 1.53 and the damping ratio is 0.054. The speed of the flow is varied to enable detailed examination of coupling phenomena at, above, and below the classic *lock-in* regime.

The focus of ongoing research and concomitant findings to date can best be described in the context of the frequency and amplitude response plot of the cylinder shown in Figure 3. This plot includes the results of two independent experiments in which the tunnel speed was varied and the frequency of vortex shedding along with cylinder amplitude were measured. In this graph, parameters have been nondimensionalized by cylinder natural frequency, free stream velocity, and cylinder diameter. The straight solid line passing through the plot is the non-dimensional Strouhal frequency.

Careful examination of Figure 3 permits identification of four regimes in the freely oscillating cylinder experiment. For $Uf_nD < 3.8$, there is no appreciable cylinder motion in response to the vortex shedding. This is also true for $7.6 > Uf_nD > 8.4$. The *classic* lock-in regime, characterized by shedding of patterns of vortices at the cylinder natural frequency over a range of speeds, is located in the range, $5.6 < Uf_nD < 7.6$. The fourth regime, which will be referred to as *reverse* lock-in, is located in the range, $3.8 < Uf_nD < 5.6$. This regime includes the maximum amplitude response condition and is characterized by a departure of the frequency response data from the Strouhal frequency.



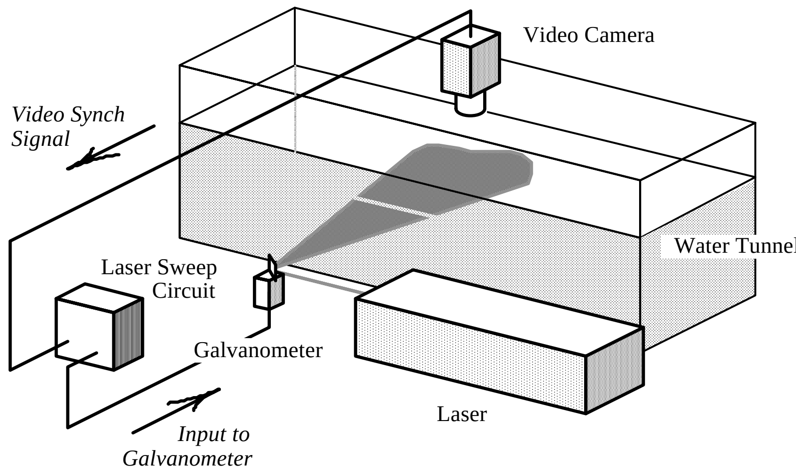


Figure 1. Schematic drawing of the Cylinder with leaf spring attachment.

Figure 2. Oblique view drawing of the experimental the setup including optics, electronics, and water tunnel test section.

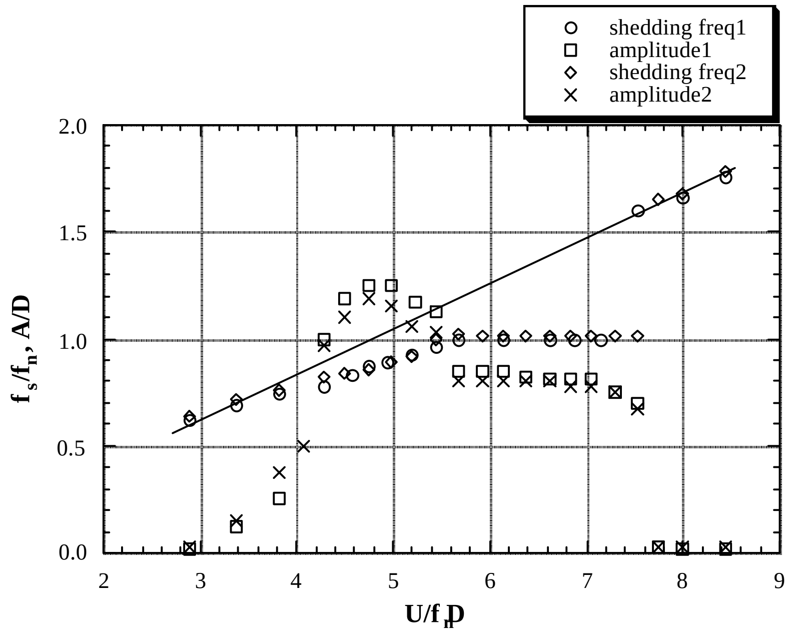


Figure 3. Frequency and amplitude response curve for the freely vibrating cylinder experiment. Note the reverse lock-in regime to the left of the classic lock-in regime.

The distinction between *classic* and *reverse* lock-in regimes can be made in terms of cause and effect between fluid flow and cylinder motion. In the reverse lock-in case, the cylinder appears to be driven by vortex shedding. As the vortex formation length decreases and vortex strength increases, low-pressure vortex cores begin to *pull* on the cylinder. This effect is most dramatic for the maximum amplitude response case in which cylinder motion and vortex shedding appear to be in phase at a frequency ~0.8 times the cylinder natural frequency. In the classic lock-in regime, the cylinder motion appears to drive the vortex shedding. Individual vortices are far less coherent and often appear uncoupled to the cylinder. LIF studies and subsequent DPIV measurements indicate the existence of patterns of vortices, which periodically recur at the cylinder natural frequency.

The concept of a pseudo-pressure gradient has been developed to account for the added vorticity flux generated by the cylinder motion. In brief, the acceleration of the cylinder can be interpreted as a *pseudo* pressure gradient, which generates vorticity in the cylinder boundary layer. Detailed analysis is in progress to correlate this generation mechanism with the observed fluid-structure interactions. Use of the new DPIA program coupled with a control volume examination of energy transport in the flow will also be used in direct support of the reduced order analytical model formulation.

IMPACT/APPLICATION

A deeper understanding of fluid-structure interaction can have extensive impact on both military and civilian technology. Flow-induced vibration is a major component in structural fatigue and failure, and in noise generation, for example. The dynamics of flow-induced vibration affects the design of everything from aircraft and skyscrapers to ships. Uncertainties associated with this interaction are difficult to quantify and require a deeper understanding as structures are required to operate in more severe environments under stricter constraints. The variational mechanics framework is a very

exciting one, in that it provides us with a high level perspective on the physical processes (solid and fluid and the interaction) and how to model them.

TRANSITIONS

Scientific findings from this investigation are being disseminated through refereed journal articles as well as international conference papers. In addition, the PIs have been invited to give seminars on this research. Direct transitions of this work to the Navy are occurring through ongoing, related collaborations with the Naval Undersea Warfare Center (NUWC) and the Naval Surface Warfare Center (NSWC); these are outlined in the following section. There is also an ongoing interaction with the Naval Research Laboratory (NRL) which may potentially serve as an additional transition mechanism for this work.

RELATED PROJECTS

There are two ongoing interactions with Navy laboratories that are directly relevant to this program. The first is a collaboration with NUWC on the dynamics of multiline towed sensor arrays. A flow visualization study in the wake of a lateral force device was recently completed at Rutgers; discussions defining further research directions are underway. The second collaboration is with the Structural Acoustics and Hydroacoustics Branch at NSWC. Fluid-structure interactions are being examined in the context of flow noise generation.

PUBLICATIONS

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